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EFFECTS OF IMPERVIOUS COVER AT MULTIPLE SPATIAL SCALES ON COASTAL WATERSHED STREAMS[1]

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ABSTRACT: The spatial scale and location of land whose development has the strongest influence on aquatic ecosystems must be known to support land use decisions that protect water resources in urbanizing watersheds. We explored impacts of urbanization on streams in the West River watershed, New Haven, Connecticut, to identify the spatial scale of watershed imperviousness that was most strongly related to water chemistry, macroinvertebrates, and physical habitat. A multiparameter water quality index was used to characterize regional urban nonpoint source pollution levels. We identified a critical level of 5% impervious cover, above which stream health declined. Conditions declined with increasing imperviousness and leveled off in a constant state of impairment at 10%. Instream variables were most correlated ($0.77 \leq |r| \leq 0.92$, $p < 0.0125$) to total impervious area (TIA) in the 100-m buffer of local contributing areas (~5-km^2 drainage area immediately upstream of each study site). Water and habitat quality had a relatively consistent strong relationship with TIA across each of the spatial scales of investigation, whereas macroinvertebrate metrics produced noticeably weaker relationships at the larger scales. Our findings illustrate the need for multiscale watershed management of aquatic ecosystems in small streams flowing through the spatial hierarchies that comprise watersheds with forest-urban land use gradients.

(KEY TERMS: nonpoint source pollution; impervious cover; macroinvertebrates; water quality index; geographic information system; spatial scale; watershed management; riparian buffers.)

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INTRODUCTION

Urbanization threatens the water quality and biotic integrity of streams. Covering land with impervious surfaces – roads, parking lots, buildings, and sidewalks – creates many direct and indirect deleterious impacts on aquatic ecosystems (see review by Paul and Meyer, 2001). Impervious cover disrupts the natural hydrologic cycle (Booth, 1991), often leads to unstable stream channel morphology (Leopold *et al.*, 1964) requiring the use of bank armoring to stop natural channel migration near structures, increases urban nonpoint source (NPS) pollution delivery (Bhaduri *et al.*, 2000; Nelson and Booth, 2002; USEPA, 2002), and degrades instream habitat and biota (Karr and Chu, 2000). The impervious cover problem, which will likely expand with the increase

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in sprawl around many cities in the United States (Ewing *et al.*, 2002) is a continuing threat to aquatic ecosystems.

Much of the stream monitoring research suggests water quality (Brabec *et al.*, 2002), and instream habitat (Wang *et al.*, 1997) are impaired and macroinvertebrates (Schueler, 1994; CWP, 2003) and fish (Wang *et al.*, 2001b; Miltner *et al.*, 2004) sensitive to habitat degradation begin to disappear in the vicinity of 10% impervious cover. Some studies (e.g., Stepenuck *et al.*, 2002; Wang and Kanehl, 2003) have observed the decline of macroinvertebrate communities at even lower levels of imperviousness. Even with the consistent reporting of a critical threshold of percent impervious cover where stream conditions decline (Beach, 2002; CWP, 2003), more work is needed to explore physical, chemical, and biological components of streams across a continuum (e.g., Booth *et al.*, 2002) of development levels. In addition, more research is needed to establish baseline conditions in urban streams as they are typically the target of stream restoration efforts (Morley and Karr, 2002). Our study adds to the previous investigations of the relationships between imperviousness and instream conditions because it expands the geographic range of such work, adds to the relatively few studies that have considered the change in stream conditions in urbanizing forested watersheds with little agricultural activity, and includes a comprehensive water quality study to complement biomonitoring.

Although biological monitoring is currently a popular tool for assessing the biotic integrity of stream habitat (Karr and Chu, 2000), many federal and state agencies still rely on water chemistry data to guide regulatory and land use management decisions (Trench and Kiesman, 1998). Multiparameter water quality indices have been used to serve a variety of functions by providing a simple, objective way of judging and ranking water quality that is more robust than any individual parameter (see review by Ott, 1978). The early indices were primarily used for comparing the quality of waters with regards to sanitary sewage and point source discharges (e.g., Horton, 1965). Other uses of water quality indices include examining recreation potential (Cude, 2001) and the effects of acid mine drainage (Gray, 1996). Additionally, several indices (e.g., Couillard and Lefebvre, 1986; Said *et al.*, 2004) have been developed to identify and help manage broad pollution sources as NPS pollution emerged as an important water quality management issue. The water quality index (WQI) presented in this study has been tuned to our study region to investigate the impacts of urban NPS pollution in small coastal watersheds in New England. Our index may also be used to evaluate the effectiveness of best management practices and stream restoration efforts to mitigate urban water quality impacts to streams.

Studying the effects of impervious cover is essential to understand the relationships between landscape and instream variables, yet alone does not offer direct management strategies to protect aquatic ecosystems as development sprawls towards more natural areas. To this end, it is necessary to explore the spatial scale and distribution or "spatial perspective" (Strayer *et al.*, 2003) of land cover that has the greatest influence on water quality and biological communities in a stream (Hunsaker and Levine, 1995; Allan *et al.*, 1997). Early work exploring the influence of land use patterns on stream health primarily focused on water quality in agricultural catchments (e.g., Omernik *et al.*, 1981). With more recent emphasis on protecting stream habitat and biota and the availability of geographical information systems (GIS) making rapid land use studies possible, the number of peer-reviewed publications reporting on the relationships between instream conditions and land use variables at multiple spatial scales has increased over the passed several years (e.g., Roth *et al.*, 1996; Allan *et al.*, 1997; Lammert and Allan, 1999; Sponseller *et al.*, 2001; Wang *et al.*, 2001a; Morley and Karr, 2002; Meador and Goldstein, 2003; Strayer *et al.*, 2003; Weigel *et al.*, 2003; Black *et al.*, 2004; Booth *et al.*, 2004; Potter *et al.*, 2004; Townsend *et al.*, 2004). A common finding of these works is the identification of multiple scales of interaction between streams and the surrounding landscape, although the details of the results vary.

Numerous studies show that local and riparian land use, and instream variables measured at the reach scale, are better predictors of biotic condition than regional land use (e.g., Lammert and Allan, 1999; Sponseller *et al.*, 2001; Wang *et al.*, 2001a; Roy *et al.*, 2003; Strayer *et al.*, 2003; Booth *et al.*, 2004). In addition, regional land use seemed to be more closely related to stream water quality, particularly nutrient concentrations (Sponseller *et al.*, 2001; Strayer *et al.*, 2003) and the level of hydrologic flow alteration (Booth *et al.*, 2004). However, Roth *et al.* (1996) found macroinvertebrate metrics to be more strongly correlated to regional than local land use, while Morley and Karr (2002) concluded that both spatial scales were equally important. Differences in these results are likely attributed to the variations in study design (Allan and Johnson, 1997) and geographic location (Potter *et al.*, 2004). More work is needed to create a larger set of consistent results to achieve the goal of establishing land use management strategies to protect water quality, physical habitat, and stream biotic integrity.

Several of the recent studies investigating the relationships between instream condition and land use at multiple spatial scales have used third party datasets such as those available through the U.S. Geological Survey's National Water Quality Assessment Program and the U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program. Black *et al.* (2004) and Weigel *et al.* (2003) saw little difference in the amount of variation in macroinvertebrate metrics explained by variables at different spatial scales. Meador and Goldstein (2003) looked over large geographic scales (i.e., across the U.S.) and found that physicochemistry and riparian condition are better indicators of fish community condition than basin land use. Empirical modeling by Strayer *et al.* (2003) produced results that are in agreement with the several primary data studies indicating that the riparian corridor is most important for predicting biotic condition, while land cover over the whole watershed is the best predictor of water quality. The line of research relating instream conditions to land use at multiple spatial scales using third party data has produced a variety of conclusions that warrant further study.

The primary objectives of this study are twofold: (1) to explore the relationships between instream variables – water quality, macroinvertebrate assemblages, and physical habitat – and impervious cover across an urban-forest gradient; and (2) to use GIS to study the relationship between instream conditions and the spatial perspective of impervious cover in a nested watershed study in a New England, U.S. coastal watershed. We present a multiparameter WQI tuned to indicate the level of urban-derived NPS pollution in our study region. This work constitutes the initial findings of an interdisciplinary research program designed to locate hotspots of urban NPS pollution, analyze the effects of urbanization on instream biological communities, and create a land management plan to protect water resources and aquatic habitat in the West River watershed, New Haven County, Connecticut.

MATERIALS AND METHODS

Study Site

The West River flows south for approximately 30 km and empties into New Haven Harbor on Long Island Sound (Figure 1). The work presented in this study focuses on freshwater streams in the middle and upper watershed. A prominent basaltic ridge runs north south down much of the center of the watershed separating the drainage into eastern and western subwatersheds. Bedrock geology generally consists of shale and sandstone to the east and schist and gneiss to the west, with soils composed of compacted glacial till with small deposits of alluvial sand and gravel along watercourses. Permitted municipal or industrial point discharges do not exist on the upper West River or its tributaries and thus NPS pollutants such as fertilizers, pesticides, bacteria, sediment from construction sites, road salt, and leaking oil from automobiles are the primary detriments to water quality in the West River watershed. Census data indicates that approximately 135,000 people live in the West River watershed (Census 2000, U.S. Census Bureau), and the majority resides in the lower portion. The study site thus offers a continuum of development suitable for studying urban impacts on streams.

Land use of the West River watershed (Civco *et al.*, 1998) is dominated by forest (Table 1), with the majority of this area located in the northern part where impervious cover is minimal (Figure 1). Much of the remaining watershed is a combination of commercial, industrial, and high to medium density residential areas. This urban land use, which contains considerable amounts of impervious cover, is abundant in the central and southern portions of the watershed in the vicinity of the City of New Haven (Figure 1). Less than 10% of the watershed area is used for agriculture (Table 1).

Impervious Cover

We compared instream variables to impervious cover at four spatial scales – watershed, local contributing area, and the 100-m riparian buffer in each of the two (Figure 2). Watersheds, the complete contributing drainage areas upstream of each sample site, were manually delineated with GIS software (ArcView Version 3.2; Environmental Systems Research Institute, Inc., Redlands, CA) by altering portions of an existing coverage of drainage divides for the State of Connecticut (Map and Geographic Information Center, University of Connecticut, Storrs, CT; Accessed via http://magic.lib.uconn.edu/) using digitized U.S. Geological Survey topographic maps (1:24,000). Watershed divides were verified in the field. Watersheds were truncated to approximately 5-km^2 *local contributing areas* immediately upstream of sample sites based on topography and changes in surface hydrology (e.g., the presence of a tributary or pond). The resulting local contributing areas had a mean area of 4.5 ± 0.5 km^2, as compared with 17.1 ± 6.4 km^2 for the complete upstream watersheds. With land management in its current form often taking place locally within municipalities (Allan *et al.*, 1997), we believe the local contributing areas

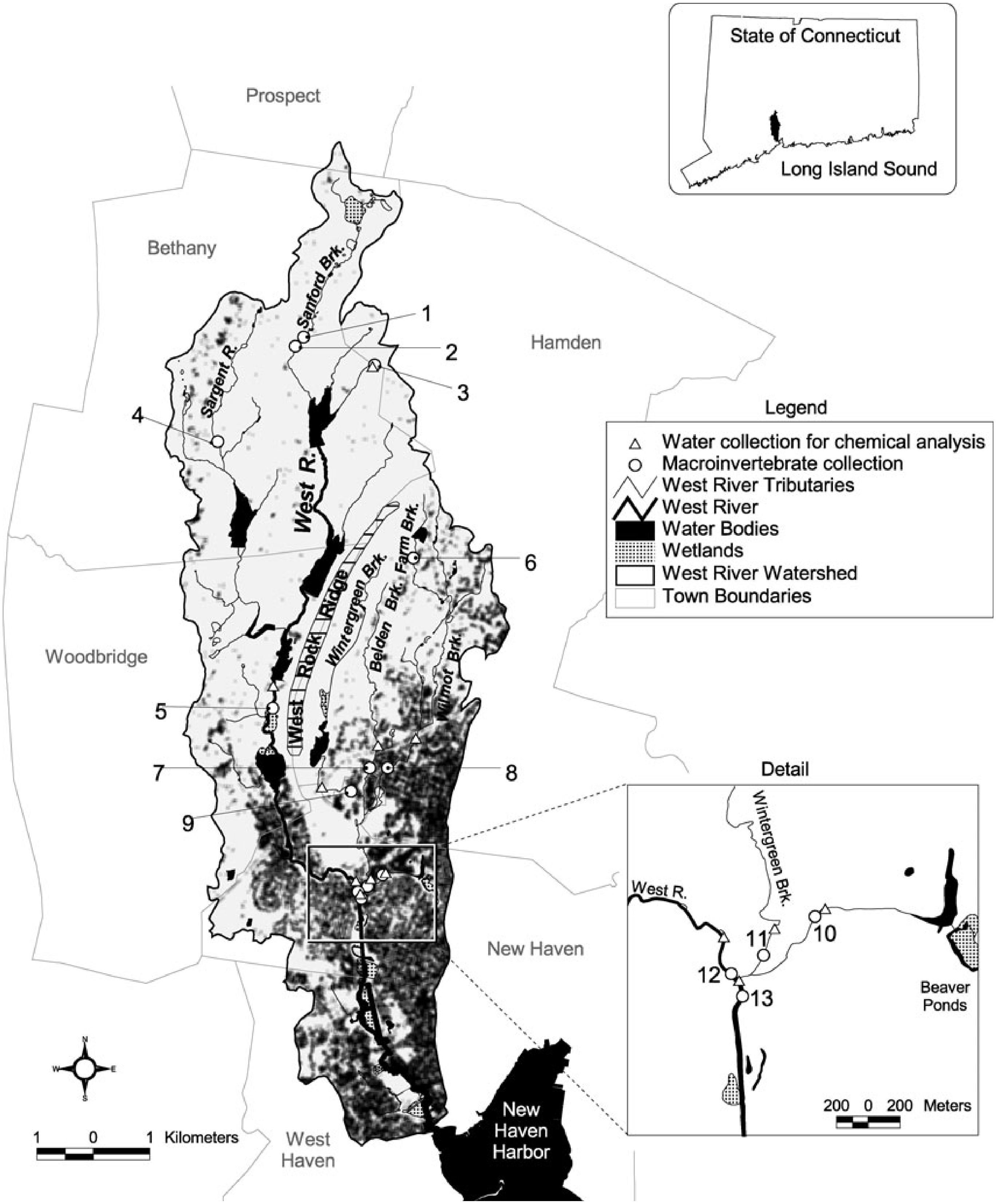

FIGURE 1. Sample Sites in the West River Watershed, New Haven County, Connecticut. Background shading represents impervious cover in each 30 × 30-m pixel with darker areas indicating more imperviousness (Flanagan and Civco, 2001). Detail shows the confluence of Wintergreen Brook and the outlet from Beaver Ponds with the West River.

TABLE 1. Land Use in the West River Watershed, New Haven County, Connecticut.

Land Use	Area (km^2)	Proportion (%)
Forest	46.6	52.8
Commercial, industrial, and high to medium density resident	21.5	24.3
Low density residential	9.8	11.1
Agriculture (<50% soil exposure)	6.0	6.7
Water	2.6	2.9
Scrub and shurb	0.8	0.9
Wetland	0.8	0.9
Agriculture (>50% soil exposure)	0.3	0.3

represent an important spatial scale to investigate in addition to watershed (i.e., regional) and riparian (i.e., near stream) scales. The 100-m riparian buffers in both the watersheds and local contributing areas were delineated with a GIS buffering tool (Xtools Version September 15, 2003; Oregon Department of Forestry, Salem, OR; Accessed via http://www.odf.state.or.us/divisions/management/State_forests/XTools.asp).

Impervious cover was quantified with Landsat Thematic Mapper (TM) satellite imagery having 30-m pixel resolution (Flanagan and Civco, 2001). To account for surfaces with dimensions less than 30 m, impervious cover determined directly from the TM satellite image was enhanced with artificial neural networks of buildings, roads, houses, driveways, parking lots, and sidewalks obtained from high-accuracy planimetric data layers and urban-related land use types from previously classified TM imagery (Civco *et al.*, 1998). Percent total impervious area (TIA) was calculated by clipping the impervious cover GIS layer with watershed, local contributing area, and buffer boundaries. The area occupied by each of 10 impervious cover percentage levels was summarized, multiplied by the appropriate percentage, and then summed to get the area of impervious cover. Percent TIA was determined by dividing by the area of the feature. Although effective, or connected, impervious area has been identified as a potentially more accurate surrogate of urban runoff than TIA (Brabec *et al.*, 2002), we elected to use TIA because it remains a popular indicator of urbanization used in stream studies (Arnold and Gibbons, 1996; Booth *et al.*, 2004).

Water Chemistry

Water was collected 14 times, monthly between June 1997 and July 1998, at nine sites spread across the major tributaries of the West River watershed (Figure 1) during baseflow. Temperature, conductivity, pH (YSI 63; YSI, Inc., Yellow Springs, OH), dissolved oxygen (YSI 85; YSI, Inc.), and turbidity (LaMotte 2020 Turbidimeter; LaMotte Company,

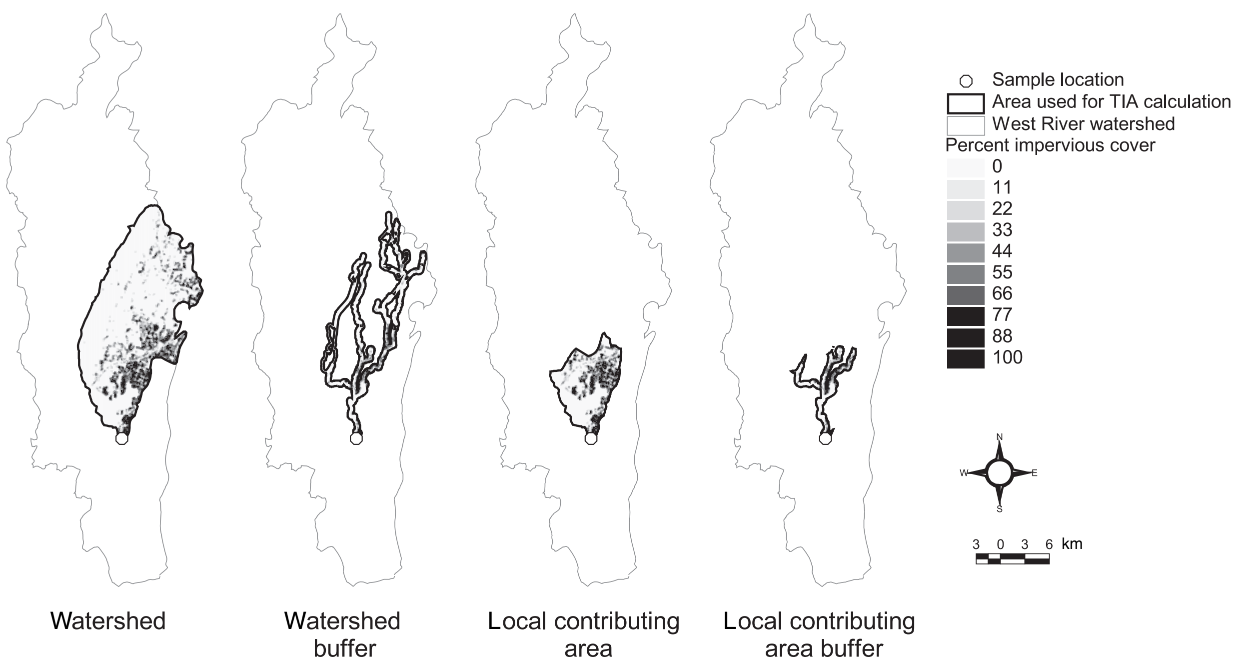

FIGURE 2. Example of Four Spatial Scales Used to Investigate Total Impervious Area (TIA) for Sample Site 11. Watershed is the complete drainage area upstream of the sample location. Watershed buffer is the 100-m riparian buffer in the watershed. Local contributing area is approximately 5 km^2 immediately upstream of the sample site. Local contributing area buffer is the 100-m riparian buffer in the local contributing area.

Chestertown, MD) were measured at each site. One-liter, acid-washed sample bottles were rinsed three times with stream water prior to sample collection. Samples were preserved on ice and transported to the laboratory within 3 h for analysis of acid neutralizing capacity via potentiometric (gran) titration (Morel and Hering, 1993) and suspended particulate matter by gravimetric filtration (0.45-μm filter; Millipore, Billerica, MA). Filtered water was analyzed for dissolved anions (i.e., chloride, nitrate, sulfate, and phosphate) via ion chromatography (Dionex AS-14 anion exchange column; Dionex Corporation, Sunnyvale, CA), cations (i.e., sodium, potassium, calcium, and magnesium) by inductively couple plasma-atomic emission spectrometry (Optima 3000; Perkin-Elmer, Wellesley, MA), and dissolved organic carbon by the high temperature combustion infrared method (Shimadzu TOC5000; Shimadzu Corporation, Kyoto, Japan). Total nitrogen was measured in unfiltered water by alkaline persulfate oxidation followed by ion chromatography. Water for measuring fecal coliform indicator bacteria was collected separately in sterile containers, preserved on ice for incubation within 4 h of collection, and incubated according to EPA method No. 1103.1. All samples were analyzed using current standard methods (Clesceri *et al.*, 1998).

We tuned a common format of existing water quality indices to meet the need for a water chemistry-based management tool in our study region to quantify NPS pollution levels in partially urbanized watersheds. Our multiparameter WQI is a normalized average of seven parameters (total dissolved solids, suspended particulate matter, fecal coliform, nitrate, phosphate, the chloride to sulfate ratio, and the nitrate to total nitrogen ratio) and is calculated by

$$\mathrm{WQI} = 10 - \left(\frac{10}{7}\right) \times \sum_{i=1}^{n} \left(\frac{P_i}{P_{i,\max}}\right) \quad (1)$$

where P_{i} is the average of parameter i for all 14 samples collected over the year at each site, $P_{i,\max}$ is the highest mean value of parameter i at any site in the region during the course of the study, and n represents the number of parameters used in the index (n = 7). As all samples were collected under baseflow conditions when water chemistry tends to be more stable than during event flow, use of either the mean or median yielded similar index values. The WQI is scaled from zero to ten, with higher WQI values indicating higher water quality.

We included measures of fecal coliform bacteria, nutrients, and suspended particulate matter in the WQI due to their common presence in NPS pollution (Still, 1991). These parameters are also represented in early indices used to investigate sanitary pollution (Brown *et al.*, 1970; Landwehr *et al.*, 1975) illustrating that similarities exist between sanitary sewage and urban NPS pollution. Anion data revealed larger chloride to sulfate ratios, likely the result of road salt applications in winter, at sites where higher concentrations of other NPS pollutants were found. In addition, the ratio of nitrate to total nitrogen was included in the WQI because streams effected by logging, agriculture, and urbanization have been shown to export more nitrate than organic nitrogen (Likens and Borman, 1995; Petersen *et al.*, 2001). Dissolved oxygen concentration was excluded from the WQI because oxygen depletion did not parallel other common indicators of degraded water quality. Oxygen levels at our sites were likely a function of physical factors such as re-aeration rates associated with turbulent riffles. We elected to use the arithmetic mean of selected parameters because this construct has been shown to effectively discriminate between high and low water quality (Stambuk-Gilijanovic, 2003).

Macroinvertebrates

Macroinvertebrates were sampled once in spring 1999 at 13 sites, 3 on the main stem of the West River and 10 on tributaries (Figure 1). Sampling sites were located in the nearest riffle or run habitat to the water chemistry sites to facilitate comparing chemical and biological data. We collected macroinvertebrates only from riffles and runs to minimize the natural variation exhibited by assemblages associated with different microhabitats (Parsons and Norris, 1996). In addition, the gravel and cobble substrate of riffle/run habitats are the dominant habitat type in the study streams, and thus this sampling approach provides a representative sample of stream reaches (Barbour *et al.*, 1999). All collections were performed during baseflow conditions, and no large floods occurred during the spring 1999 before or during the sampling period.

Macroinvertebrates were collected from 930-cm^2 plots of the streambed by disturbing movable substrate and allowing dislodged organisms to drift into a D-frame dip net (Turtox, 30.5-cm wide mouth, 500-μm mesh size; Wildlife Supply Company, Buffalo, NY) placed immediately downstream. Plot sizes were estimated by the (1.0 foot) width of the dip net. Twelve replicates were collected from riffles and runs, while moving upstream over a 100-m reach. All collected material was combined and placed in a bucket, rinsed over a 500-μm sieve to remove fine particles, and samples preserved in 80% ethanol. In the laboratory, subsamples of approximately 200 organisms were randomly selected (Barbour *et al.*, 1999) and insects were identified to genera, except the midges (Chironomidae), which were determined to family. Pupae were excluded from the project as they comprised less than 10% of collected organisms and were represented by the larvae.

The multimetric USEPA Rapid Bioassessment (RBP) (Barbour *et al.*, 1999) was used to quantify macroinvertebrate assemblages. We determined percent similarity to the nearby (approximately 10 km away) Eightmile River regional reference site used by the Connecticut Department of Environmental Protection. As prescribed by Barbour *et al.* (1999), a score (0-6) was assigned based on the percent similarities, and descriptive impairment categories were determined by summing the scores for taxa richness, EPT index (EPT) – the number of genera of Ephemeroptera, Plecoptera, and Trichoptera (i.e., mayflies, stoneflies, and caddisflies), percent dominant taxa, the EPT to Chironomidae ratio, the scraper to collector-filterer ratio, community loss, and Hilsenhoff biotic index (HBI) – a weighted pollution tolerance index (Hilsenhoff, 1987).

Physical Habitat

Stream order and discharge were determined and, in conjunction with watershed and local contributing area size, used to investigate potential sources of natural variation of water chemistry (Hem, 1992) and macroinvertebrate communities (Vannote *et al.*, 1980). Stream order (Strahler, 1952) was identified from GIS and U.S. Geological Survey topographic maps (1:24,000) and verified in the field. Instantaneous stream discharge was measured at representative channel cross-sections located within each of the macroinvertebrate sample reaches wherein velocity was measured using an electromagnetic flow velocity meter (Flo-Mate; Marsh-McBirney, Frederick, MD) at 0.6 times depth (Leopold *et al.*, 1964). We performed the USEPA's qualitative habitat assessment (Barbour *et al.*, 1999) at each macroinvertebrate sample site to determine the structure and quality of physical habitat. This assessment includes: substrate and cover, embeddedness, water velocity and depth regime, sediment deposition, channel flow status, channel alteration, riffle frequency, bank stability, bank vegetation, and width of vegetated riparian zone. Each category is scored on a 0-20 scale and then summed for a cumulative habitat score and expressed as a percentage of the maximum score (i.e., 200).

Data Analysis

We explored patterns relating instream variables and impervious cover. Variables were transformed to normalize distributions and linearize relationships for subsequent analysis. Pearson correlation (SAS Version 8.1, proc corr; SAS Institute, Inc., Carey, NC) was used to explore the relationships between variables, with significance levels adjusted ($p < \alpha/K = 0.1/8 = 0.0125$) using the Bonferroni correction (Sokal and Rohlf, 1995) to limit the error rate associated with family-wise correlation testing (Van Sickle, 2003). Stepwise redundancy analysis (Canoco Version 4.53; Wageningen, The Netherlands) was performed to observe the relationships between various combinations of response (i.e., instream) and explanatory (i.e., impervious cover at each scale, watershed area, local contributing area, and discharge) variables (ter Braak and Smilauer, 1998; Leps and Smilauer, 2003). Response variables were centered and standardized (i.e., mean of 0 and variance of 1) to account for different units of measurement. The entry of explanatory variables into the model was performed interactively in descending order of the amount of improvement to the model, and at a significance level of 0.1, using partial Monte Carlo permutation testing ($n = 499$). Previously entered variables were used as covariates to avoid redundancy associated with correlated variables. We used triplot ordination diagrams to investigate correlations (Leps and Smilauer, 2003).

RESULTS

Impervious Cover

Total impervious area in the watersheds draining to each macroinvertebrate collection site varied between 0 and 61% (Table 2). Seven of the watersheds had little impervious cover (TIA <5%), five had moderate amounts of impervious cover (5% < TIA < 20%), and one watershed was highly impervious (TIA >60%). TIA in the 100-m riparian buffer within each watershed was similar to that in the entire watershed ($r = 0.92$, $p = 0.000$), as was the case for the 100-m buffer in the local contributing area and the local contributing area itself ($r = 0.90$, $p = 0.000$). Local contributing area imperviousness was substantially larger than that in the corresponding watershed for four of the sample sites (8, 11, 12, and 13). Imperviousness at these sites was also larger in the 100-m buffer in the local contributing areas than the buffers in the larger watersheds (Table 2). The TIA analysis indicates increased local imperviousness at several of the downstream sample sites as compared with the land cover composition in the complete upstream watersheds.

TABLE 2. Summary of Water Chemistry, Macroinvertebrate, Physical, and TIA Variables.

	Variable **Site:**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Water Chemistry	TDS (mg/l)	n/a	n/a	19	n/a	50	n/a	81	97	37	120	114	72	118
	SPM (mg/l)	n/a	n/a	3.8	n/a	1.2	n/a	1.6	2.0	3.1	5.0	6.7	3.6	4.8
	Fecal coliform (#/100 ml)	n/a	n/a	0	n/a	23	n/a	209	210	20	441	305	652	540
	NO_3^- (μM)	n/a	n/a	1	n/a	2	n/a	70	69	7	78	75	18	65
	PO_4^{3-} (μM)	n/a	n/a	0.0	n/a	0.0	n/a	1.2	0.8	0.0	0.2	0.1	0.3	0.2
	Cl^-/SO_4^{2-} (1)	n/a	n/a	0.9	n/a	3.7	n/a	3.1	4.6	1.8	6.1	5.7	4.5	5.2
	NO_3^-/TN (%)	n/a	n/a	5	n/a	13	n/a	96	77	28	55	51	58	66
	WQI*	n/a	n/a	8.7	n/a	8.0	n/a	3.4	3.4	7.9	2.6	3.0	4.3	2.7
Macroinvertebrate	Taxa richness	33	31	12	29	15	15	20	11	34	15	13	11	10
	EPT index	19	18	7	11	8	3	9	3	22	2	4	3	1
	Dominant taxa (%)	24	23	38	27	73	42	48	38	18	36	63	69	68
	EPTChironomidae ratio	3.3	3.4	1.5	2.6	2.4	0.1	0.5	0.5	7.4	0.1	0.3	0.1	0.0
	Scraper: collector-filterer ratio	2.5	1.4	0.0	2.3	0.0	0.0	1.2	1.6	1.6	5.8	0.1	0.3	0.5
	Community loss	0.6	0.5	2.1	0.7	1.6	1.7	1.1	2.1	0.6	1.5	1.8	2.3	2.6
	HBI	3.6	3.2	3.9	3.4	4.2	7.0	5.3	5.9	3.1	6.1	6.4	7.1	7.2
	RBP multi-metric score (%)†	70	75	20	55	15	10	35	25	80	30	15	20	20
	RBP Impairment Category‡	sli	sli	mod-sev	sli	sev	sev	mod	mod	non-sli	mod	sev	mod-sev	mod-sev
Physical	Stream order	1	1	1	1	3	1	2	2	2	1	3	3	4
	Discharge (m^3/s)	0.3	0.1	0.0	0.1	0.4	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.5
	$Area_{watershed}$ (km^2)	4.7	4.8	0.1	3.8	36.6	1.3	3.6	10.2	5.2	4.8	22.1	48.7	75.9
	$Area_{local}$ (km^2)	4.7	4.8	0.1	3.8	5.0	1.3	3.6	6.7	5.2	4.8	5.7	6.7	5.4
	Habitat score (%)	95	91	81	92	86	45	51	53	77	34	42	38	46
Impervious	$TIA_{watershed}$ (%)	1	1	0	4	1	1	11	20	3	61	16	6	12
	$TIA_{buffer\ watershed}$ (%)	1	1	0	0	1	5	14	15	3	38	15	5	10
	TIA_{local} (%)	1	1	0	4	1	1	11	27	3	61	28	28	34
	$TIA_{buffer,local}$ (%)	1	1	0	0	3	5	14	20	3	38	30	41	38

Notes: *WQI was calculated from the seven metrics listed above the WQI as described in the methods.

†The RBP multi-metric score was calculated from the seven metrics listed above the RBP score and impairment categories were assigned according to Barbour *et al.* (1999).

‡Impairment categories: non-sli = non/slight (80-83%), sli = slight (55-79%), mod = moderate (22-50%), mod-sev = moderate/sever (18-21%), sev = severe (<18%).

TIA = total impervious area, WQI = The water quality index, RBP = rapid bioassessment protocols, n/a = water quality was not measured at that site, subscript local = local contributing area, HBI = Hilsenhoff biotic index.

Water Chemistry

Bicarbonate, calcium, and chloride were the dominant ions in streams in the West River watershed. Water also contained moderate amounts of acid neutralizing capacity and was typically neutral to slightly basic. Suspended particulate matter and nutrients were commonly present in relatively low amounts as compared with the concentrations of the dominant ions and appeared to be linked to the presence of NPS pollution. Baseflow water chemistry at each sampling site varied little over the 1-year study period; however, water quality did vary between sites (Table 2). Three sites (3, 5, and 9) had good water quality (i.e., WQI ≥7.9), three sites (7, 8, and 12) had moderate water quality (i.e., 7.9 > WQI ≥ 3.4), and three sites (10, 11, and 13) had poor water quality (i.e., WQI < 3.4) (Thresholds represent natural breaks in the WQI score distribution). Water quality declined sharply as impervious area increased from 0 to 10%, and then plateaued at a degraded state beyond 10% imperviousness (Figure 3a).

Macroinvertebrates

The macroinvertebrate multimetric analysis revealed four sites (1, 2, 4, and 9) with macroinvertebrate assemblages similar to the healthy reference site (RBP score ≥55%, slight and non/slight impairment). All four had low levels of impervious cover, and water quality was good at the only site of the four where it was measured (Table 2). Three sites (7, 8, and 10) were somewhat different from the reference site (22% ≤RBP score <55%, moderate impairment), had moderate to degraded water quality, and TIA between 11 and 61%. Six sites (3, 5, 6, 11, 12, and 13) were degraded (RBP score ≤21%, moderate/severe and severe impairment), their local contributing areas were between 0 and 28% impervious area, and water quality varied from clean to polluted (Table 2). The multimetric score showed onset of macroinvertebrate assemblage impairment at 5% impervious watershed area and then a constant level of degradation beyond 10% imperviousness (Figure 3b).

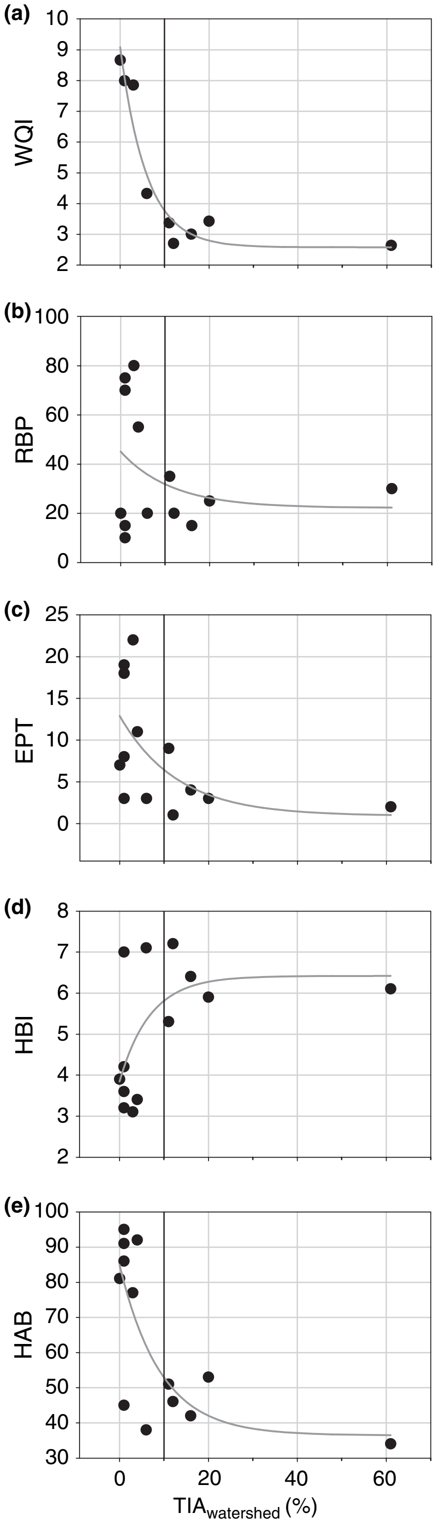

FIGURE 3. (a) Water Quality Index (WQI), (b) USEPA Rapid Bioassessment Protocol (RBP) Score, (c) EPT Index (EPT), (d) Hilsenhoff Biotic Index (HBI), and (e) Habitat Score (HAB) *vs.* Total Impervious Area (TIA) at the Watershed Scale. Equations for exponential decay (WQI, RBP, EPT, and HAB) or rise (HBI) were used to create regression lines. Solid vertical line is the 10% TIA level.

Individual metrics revealed differences in the structure and balance of macroinvertebrate assemblages (Table 2). Three study sites (1, 2, and 9) with little impervious cover in their local contributing areas contained diverse macroinvertebrate assemblages (i.e., high EPT) and had many pollution-intolerant macroinvertebrates (i.e., low HBI). Four sites (3, 4, 5, and 7) showed the decline of macroinvertebrates sensitive to pollution and assemblages had moderate diversity. Six sites (6, 8, 10, 11, 12, and 13) had homogenous collections consisting of mostly pollution-tolerant organisms. EPT index declined at 5% impervious cover (Figures 3c). Only two EPT genera that are sensitive to habitat degradation persisted above 20% imperviousness. The average pollution tolerance of the collected macroinvertebrate assemblages increased with impervious cover (Figures 3d).

Physical Habitat

Macroinvertebrate collection sites all had low instantaneous discharge (<0.1-0.5 m^3/s). Flow was observed to be intermittent only in the headwater stream tributary to Lake Bethany (site 3). Watersheds draining to each macroinvertebrate collection site had areas between 0.1 and 75.9 km^2, with a mean ± SE of 17.1 ± 6.4 km^2. Local contributing areas immediately upstream of each sample site had areas between 0.1 and 6.7 km^2 and were relatively less variable in size (mean ± SE of 4.5 ± 0.5 km^2) than the larger watersheds. We observed a mixture of habitat quality at the macroinvertebrate collection sites with the habitat score ranging from 34 to 95% (Table 2). Habitat quality dropped off above 5% impervious cover and was consistently in a degraded state above 10% imperviousness (Figure 3e).

Imperviousness at Multiple Spatial Scales

Correlations indicated stronger relationships between instream variables and impervious cover at smaller, more local, spatial scales (Figure 4). For each instream variable, the relationship with TIA in the 100-m buffer of the local contributing area was strongest ($0.77 \leq |r| \leq 0.92$), whereas imperviousness at the watershed scale produced the weakest relationships ($0.53 \leq |r| \leq 0.80$). Water and habitat quality had a relatively consistent strong relationship with TIA across each of the four spatial scales of investigation, whereas macroinvertebrate metrics produced noticeably weaker relationships at the larger scales. Correlations between both water quality and habitat score and TIA in the 100-m buffer in the local scale were strongest ($|r| \sim 0.92$).

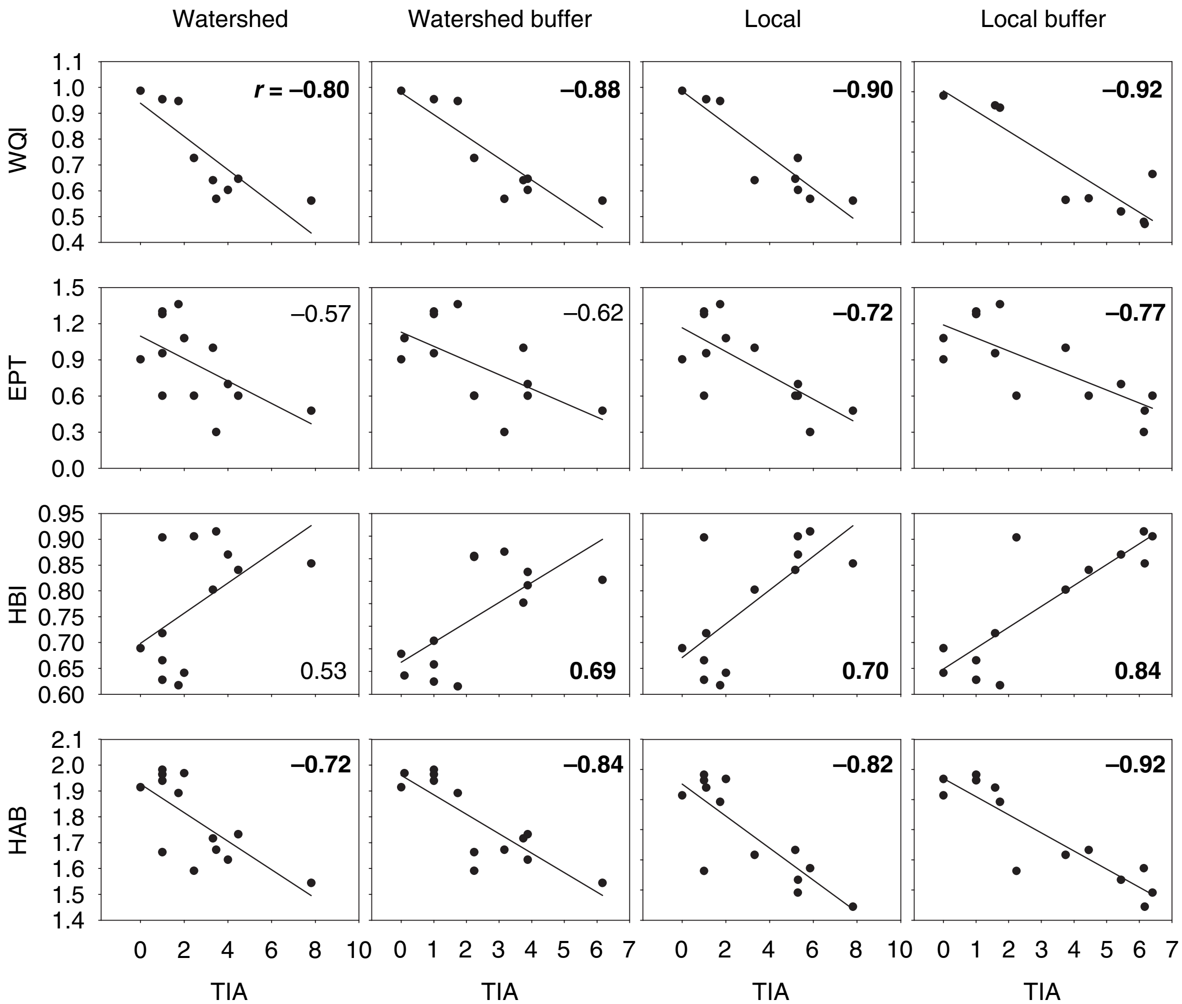

FIGURE 4. Water Quality Index (WQI), EPT Index (EPT), Hilsenhoff Biotic Index (HBI), and Habitat Score (HAB) *vs*. Percent Total Impervious Area (TIA) at Varying Spatial Scales. "Local" represents local contributing area. Pearson correlation coefficient (r) is given for each plot and bolded when statistically significant ($p < 0.0125$). WQI, EPT, HBI, and HAB were $\log_{10}(x + 1)$ transformed and TIA variables were square root transformed. Lines on each plot are to assist viewing the trend in the data and not intended for predictive purposes.

Using stepwise redundancy analysis, we found TIA in the 100-m buffer in the local contributing areas and the local contributing areas to describe the most variance (80.8%) in the set of response variables that included the WQI, EPT, HBI, and habitat assessment score (HAB) (Table 3). Impervious cover had the strongest effect in this model. The first redundancy axis (i.e., RDA1) mostly indicated impervious cover levels, whereas the second axis (i.e., RDA2) represented local contributing area (Figure 5a). HBI was strongly (negatively) correlated to WQI, EPT, and HAB all of which indicated higher pollution tolerance in the macroinvertebrate assemblage and lower water quality with increasing amounts of impervious cover in the 100-m buffer in local contributing areas. Local contributing area isolated two sample sites with the smallest area (i.e., sites 3 and 6) from the rest of the sites that were mostly dispersed along a range of imperviousness. The same general results were produced when just HBI and EPT were used as the response variables (Table 3, Figure 5b).

Total impervious area in the 100-m buffer in the local contributing areas and the area of the watersheds explained 80.2% of the variance in WQI and HAB (Table 3). Again, imperviousness had the strongest effect in the model. RDA1 increased with impervious cover and RDA2 generally increased with watershed area (Figure 5c). WQI and HAB were correlated and declined with increasing TIA in the 100-m buffer in the local contributing areas. Sample sites appeared to be distributed along a gradient of watershed size in the ordination diagram.

Total impervious area in the 100-m buffer in the local contributing areas, local contributing area, and watershed area explained 68.4% of the variance in WQI and the multi-metric macroinvertebrate score

TABLE 3. Results of RDA and Variance Partitioning.

Response Variable	Variance Described (%)	Explanatory Variables	Marginal Effect (%)
WQI, HBI, EPT, HAB	80.8	$TIA_{buffer\ local}$	76.8
		$Area_{local}$	10.8
		$TIA_{buffer,local} \times Area_{local}$	–6.8
HBI, EPT	81.8	$TIA_{buffer,local}$	81.5
		$Area_{local}$	16.8
		$TIA_{buffer,local} \times Area_{local}$	–16.5
WQI, HAB	80.2	$TIA_{buffer,local}$	61.1
		$Area_{watershed}$	5.0
		$TIA_{buffer,local} \times Area_{watershed}$	14.1
RBP, WQI	68.4	$TIA_{buffer,local}$	27.1
		Area*	26.6
		$TIA_{buffer,local} \times$ Area*	14.4

Notes: Response variables include the WQI, EPT index, HBI, HAB, and the USEPA RBP. Explanatory variables entered into the model were selected from percent TIA cover at each of the four spatial scales, watershed area, local contributing area, and flow discharge. The subscript "local" represents local contributing area. Marginal effect represents the amount of variance in the model independently accounted for by a variable. Transforms: TIA via square root and WQI, EPT, HBI, HAB, RBP, area, and flow discharge by $\log_{10}(x + 1)$.

*Area is a variable group including $Area_{watershed}$ and $Area_{local}$.

WQI = water quality index, HBI = Hilsenhoff biotic index, HAB = habitat assessment score, RBP = Rapid Bioassessment Score, TIA = total impervious area, RDA = stepwise redundancy analysis.

(RBP) (Table 3). Model effects were approximately equally distributed between TIA and a variable group containing local contributing and watershed area. RDA1 was weakly a function of TIA and watershed area, whereas RDA2 had a strong, inverse relationship with local contributing area. WQI and RBP were weakly correlated. WQI was closely linked to TIA and watershed area, and RBP was jointly dependent on each of the explanatory variables in the model.

DISCUSSION

Impervious Cover Thresholds

Our data verify nonlinear relationships characterized by thresholds between instream and impervious cover variables as suggested by Gergel *et al.* (2002). The multiparameter WQI was a good indicator of urban NPS pollution at our study site having low values in urban areas and higher values in rural locations. Of the instream variables we investigated, the WQI was the most closely related to TIA confirming the role impervious areas play in delivering NPS pollutants to urban streams (Still, 1991; Schueler, 1994; Arnold and Gibbons, 1996; CWP, 2003).

The spatial pattern of WQI values in relation to surficial landform, bedrock geology, and soil texture in the West River watershed suggests that a factor other than the natural weathering of rock was responsible for the observed water quality trends. The WQI presented in this study was more a function of NPS pollution, as indicated by impervious cover, and is thus a useful urban NPS pollution assessment tool in formerly glaciated terrain with watersheds having an urban-forest land cover gradient. Further development is needed to extend the use of the index to other landscapes, such as into watersheds dominated by urban-agriculture gradients.

The results of the water chemistry component of this work show that common NPS pollutants persist in urban streams even during baseflow conditions. This finding suggests that NPS pollution is not solely a runoff related phenomena, but impacts stream water quality throughout different hydrologic stages. We elected to investigate baseflow chemistry because previous high frequency measurements during storm events showed that while fecal coliform and suspended particulate matter concentrations fluctuated by orders of magnitude on the timescale of hours, most water chemistry parameters in streams of the West River watershed remained relatively constant (Benoit and Parrett, unpublished data).

Hilsenhoff biotic index, EPT, and RBP confirm the absence of organisms susceptible to habitat degradation above 10% impervious cover (May *et al.*, 1997; Paul and Meyer, 2001; Stepenuck *et al.*, 2002; CWP, 2003), with impairment noted at only 5% TIA (Figure 3). Healthy communities were located upstream in forested areas, and impaired communities were observed further downstream in urban areas with considerable imperviousness (Figure 6). Macroinvertebrate communities appeared to track land use patterns in a manner similar to water chemistry – sites

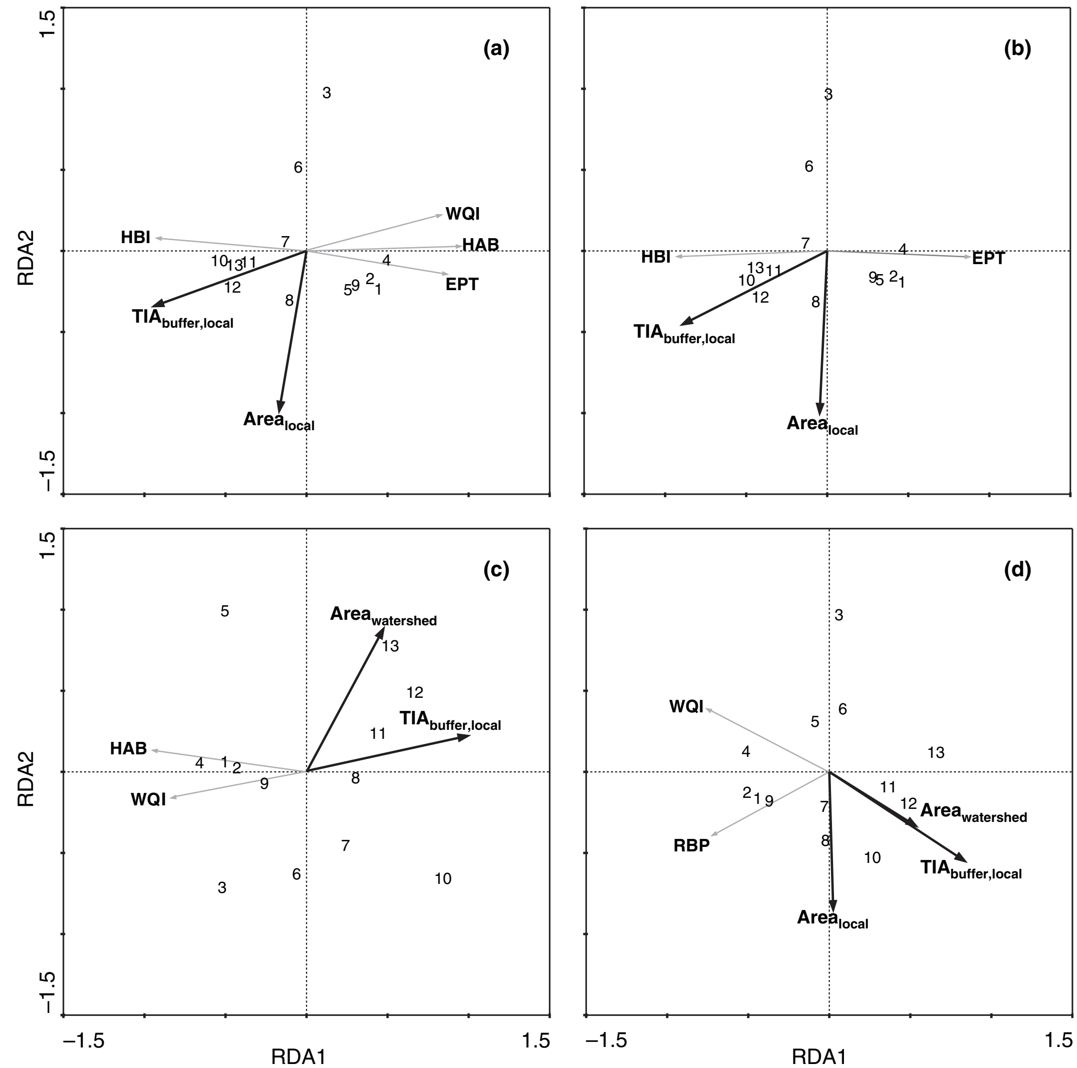

FIGURE 5. Ordination Triplots of First Two Axes (RDA1 and RDA2) Generated From Redundancy Analysis. Response variables (gray) include the water quality index (WQI), EPT index (EPT), Hilsenhoff biotic index (HBI), habitat assessment score (HAB), and the U.S. EPA rapid bioassessment score (RBP). Explanatory variables (black) entered into the models were selected from percent total impervious cover (TIA) at each of the four spatial scales, watershed area, local contributing area, and flow discharge. The subscript "local" represents local contributing area. Site numbers are located according to their ordination sample scores. Transforms: TIA via square root and WQI, EPT, HBI, HAB, RBP, area, and flow discharge by $\log_{10}(x + 1)$.

with mostly pollution-tolerant macroinvertebrates also had poor water quality. WQI was strongly correlated to EPT ($r = 0.685$, $p = 0.042$), HBI ($r = -0.876$, $p = 0.002$), and HAB ($r = 0.90$, $p = 0.001$) as is evident in the redundancy analysis triplots (Figure 5).

Although multi-metric biomonitoring metrics such as the USEPA RBP protocol are often used as biological surrogates for water quality during stream assessment (Barbour *et al.*, 1999; Karr and Chu, 2000), we found poor correlation ($r = 0.139$, $p = 0.722$) between WQI and RBP. The weak relationship could be the result of using a biological indicator multi-metric that is not specifically calibrated for our study region such as is done when using the benthic index of biotic integrity (Karr and Chu, 1999). In addition, measures of known important factors influencing macroinvertebrate assemblage characteristics such as stream bed sediment grain size distribution (Roy *et al.*, 2003) and the abundance of large woody debris (Larson *et al.*, 2001) were not part of this study. The WQI developed here would be useful for additional study comparing stream biology and fluvial geomorphology variables to a single indicator of water quality.

We view the 5% TIA critical threshold, above which we see the decline of water quality, macroinvertebrate assemblages, and physical habitat, as an important indictor of stream health. May *et al.* (1997)

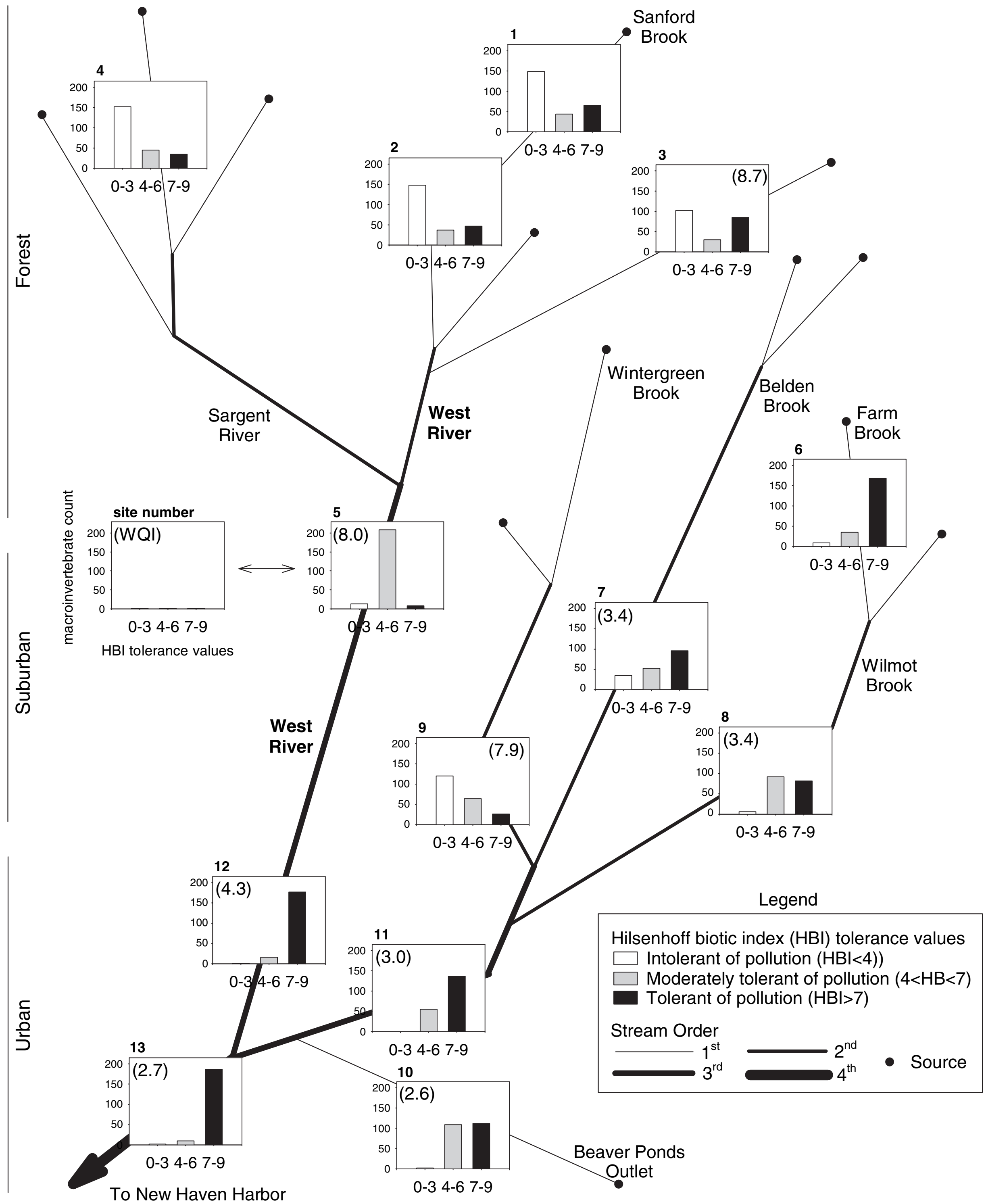

FIGURE 6. Watershed Schematic Illustrating the Distribution of Hilsenhoff Pollution Tolerance Values (Hilsenhoff, 1987; CTDEP, 2002) at Each Macroinvertebrate Collection Site. Bars on each chart represent the number of organisms within three pollution tolerance ranges: intolerant (0-3), moderately tolerant (4-6), and tolerant (7-9). Line thickness represents stream order and solid dots represent hydrologic sources. The water quality index (WQI) is presented in parentheses at sites where chemical measurements were performed. Dominant watershed land use is indicated.

observed the decline of physical stream habitat quality, a reduction in the density of large woody debris, and a decline in macroinvertebrate assemblage health in Pacific Northwest, U.S. streams as TIA increased above 5%. Morse (2001) saw a rapid decline of macroinvertebrate species abundance and EPT index at 6% TIA in 20 small Maine watersheds. A reduction in sensitive fish species has been observed in streams having watersheds with as little as 3.6% impervious cover (Booth and Jackson, 1994). Stepenuck *et al.* (2002) measured the decline of macroinvertebrate assemblage health in Wisconsin streams having watersheds with 8% imperviousness. A 7% upper impervious cover threshold was observed in 39 Wisconsin and Minnesota streams above which macroinvertebrate metrics consistently indicated poor conditions (Wang and Kanehl, 2003). Although much of the scientific literature relating stream health to watershed impervious cover indicates the presence of a threshold at the 10% level, our work is in agreement with the findings from previous studies that indicate that biotic integrity and physical habitat quality can decline at lower levels of watershed imperviousness.

Potential mechanisms of degradation at this level of impervious cover include the short-circuiting of the stream drainage network (Walsh, 2004), and the impervious cover disrupting natural flow (USEPA, 1997) and sediment regimes (Nelson and Booth, 2002). Imperviousness has also been shown to influence fluvial geomorphology variables (Booth and Jackson, 1997) that are known to have a strong influence on the composition of macroinvertebrate assemblages (Gore *et al.*, 2001). Combined with the mix of NPS pollutants often found in urban areas (Tong and Chen, 2002), a constant background stress is in place leading to long-term stream degradation. At the more local scale, vegetation removal fragments riparian corridors along urban streams limiting flood flow reduction and NPS pollution attenuation, and directly altering habitat by reducing streamside shading, organic matter inputs, and local sediment inputs (Wang *et al.*, 2002; Miltner *et al.*, 2004; Sweeney *et al.*, 2004). The repeated observation of an approximately 10% TIA threshold (Beach, 2002; CWP, 2003) is likely due to impervious cover being a common thread between the many mechanisms of urban stream degradation. Our data suggest that to protect aquatic biota in small streams, TIA should be minimized to less than 5% of total watershed area or best management practices should be implemented that achieve water quality and quantity characteristics found in watersheds with similarly low amounts of imperviousness.

Managing Impervious Cover at the Appropriate Spatial Scale

Our data show that the strength of the relationships between instream variables and impervious cover depends on the spatial scale and location that TIA is calculated and that the relationships vary for different indicators of instream conditions. Water quality and habitat had a consistently strong relationship with TIA across each of the four spatial scales [i.e., complete upstream watershed, local contributing area ($\sim$5 km^2) immediately upstream of a site, and the 100-m buffer in each], while macroinvertebrate metrics were more closely linked to imperviousness at the local scales (Figure 4). Water and habitat quality appear to be a product of regional land use, whereas the particular assemblage of macroinvertebrates seems to be more closely a function of local contributing area conditions. We thus confirm (e.g., Sponseller *et al.*, 2001; Strayer *et al.*, 2003) that the relationships between instream and watershed conditions operates at multiple scales.

Exploratory redundancy analysis indicated that the 100-m buffer in the local contributing area had the largest effect for any combination of instream variables. This finding illustrates the importance of preserving riparian forestland in headwaters for regional water quality and instream habitat protection (Perry *et al.*, 1999; Petersen *et al.*, 2001) and in mid-watershed areas to maintain healthy instream habitat and macroinvertebrate assemblages (Cummins *et al.*, 1989; Gregory *et al.*, 1991; Wissmar and Beschta, 1998). Local contributing area was also an important explanatory variable. Negative joint effects for two linear redundancy models (i.e., WQI, HBI, EPT, HAB and HBI, and EPT) indicate that the joint explanatory effects of TIA in the 100-m buffer in the local contributing areas and the area of the local contributing areas is stronger than the sum of their individual effects (Legendre and Legendre, 1998; Leps and Smilauer, 2003). This finding verifies that local contributing areas, as we have designated here, are potentially useful small-scale land management units to protect instream conditions. Watershed area was selected into the WQI and HAB model, and added to our initial result of a strong significant correlation between WQI and TIA at larger scales ($r = -0.80$, $p < 0.0125$) indicating that water quality is largely a regional management issue.

Our findings suggests that water chemistry is linked to regional land use, while macroinvertebrate assemblages are more a function of local riparian condition agrees with those of Sponseller *et al.* (2001) who found that stream water chemistry in Southern Appalachian headwater streams is more a function of larger spatial scales of non-forest (i.e., agricultural, sub-urban, and urban) land use, whereas macroinvertebrate indices most closely tracked land cover patterns at the (200-m) riparian corridor scale. Their study design was similar to ours in that they used GIS to investigate the spatial arrangement of different land uses at the local contributing area, riparian corridor, and sub-corridors of 200, 1,000, and 2,000 m scales. Strayer *et al.* (2003) found watershed land cover in the Chesapeake Bay watershed to be the best predictor of nitrate flux and land cover in the streamside corridor to be most related to invertebrate richness. This similar result adds to the robustness of our findings given their study design was substantially different from ours. Third party datasets were used to access chemical and biological data, and couple it to GIS work identifying land use at the watershed, stream corridor, and local 135-m buffer scales, where "local" was defined as a 300-m radius circle centered on a sample site. In general, studies that include both chemical and biological components often illustrate that water chemistry is most closely linked to regional land cover, while biological condition is more a function of local conditions.

Research relating stream biota to land use at multiple spatial scales regularly concludes that local areas are more important in determining the make up of instream communities. In an agriculture-dominated basin in the Midwestern United States, Lammert and Allan (1999) found local land use to be a better predictor of fish and macroinvertebrate communities than regional watershed land use. Wang *et al.* (2001a) performed a GIS spatial scale analysis and found that impervious cover in the 50-m riparian buffer, 1.6 km upstream of their sampling sites, had more influence on fish populations and baseflow in a sample of small Wisconsin streams than imperviousness at more distant watershed location. Macroinvertebrate assemblage characteristics were linked to local riparian condition in Washington State (Booth *et al.*, 2004), while investigating three scales – subbasin, riparian (200 m on each side), and local (200-m buffer, 1 km upstream). The frequent reporting of a strong relationship between instream biotic communities and riparian land use when investigating across multiple spatial scales, coupled with the known importance of riparian corridors to instream communities (e.g., Cummins *et al.*, 1989; Sweeney *et al.*, 2004), indicates the importance of effective land management near stream channels.

Contrary to these investigations, there have been several studies that have found land cover at larger scales to be more closely linked to instream communities. While studying streams in the Puget Sound Lowlands, Morley and Karr (2002) showed that most macroinvertebrate metrics were more strongly correlated to subbasin than to local (i.e., 200-m buffer, 1 km upstream) urban land cover. Within each basin though, local urban land cover was strongly related to macroinvertebrate metrics. The discrepancy in findings is potentially the result of different study designs, as our nested watershed study spanned a narrower range of watershed sizes and covered a smaller geographic extent. Allan *et al.* (1997) indicate different scales of investigation as the key factor leading to contrasting results in the same watershed – catchment land use forms the strongest relationships between habitat and biotic condition (Roth *et al.*, 1996), as opposed to local land use being the better predictor of fish and macroinvertebrate (Lammert and Allan, 1999).

Recent research investigating the effects of land cover across multiple spatial scales has employed a new type of study design using large third party datasets to consider a broad set of variables over larger geographical ranges, and thus seem better suited to identify large-scale relationships in contrast to our more local study. In fact, Potter *et al.* (2004) concluded that the importance of watershed and riparian forest cover in predicting macroinvertebrates varied by region in Carolina. Black *et al.* (2004) identified water conductivity and flow velocity to be important predictors of reach scale macroinvertebrate richness, whereas local and whole watershed scale taxa composition was a function of percent forest and agriculture land. Clearly, the variables investigated, the range of the spatial scale of the investigation, and the diverse study designs have all led to varying outcomes from research relating instream and landscape variables at multiple spatial scales (Allan and Johnson, 1997).

Potential Study Limitations

Macroinvertebrate and water quality samples were collected during baseflow, when instantaneous discharge was not influenced by storm events. This stable condition allowed for studying the relationship between the background stream condition and land cover. It is unknown if the relationships identified here will hold during event flow. A single sampling period is a potential weakness of the macroinvertebrate study, yet we believe that the collection is representative due to the absence of local and regional high flows before and during the macroinvertebrate sampling. In this scenario, resident assemblages are primarily a function of the integration of stress effects over the course of the year, and their seasonal cycles of abundance and taxa composition are predictable (Gibson *et al.*, 1996; Barbour *et al.*, 1999).

We opted to perform a single macroinvertebrate collection and thus investigate a "snapshot" of macroinvertebrate assemblages to perform this comparative study, while avoiding seasonal and annual variation. A single index period can address a range of management objectives (Barbour *et al.*, 1999), and several studies have effectively utilized single macroinvertebrate collections to explore the effects of land use (e.g., Richards and Host, 1994; Stepenuck *et al.*, 2002). Preliminary results of a recent study (Chapter 5; Schiff, 2005) employing a similar study design produced comparable results to the current study – macroinvertebrate health and local habitat quality was most closely related to local land cover, while water quality was more a function of regional land cover.

MANAGEMENT STRATEGIES

The findings presented in this study have important ramifications for land use management in small streams with developing watersheds having a forest-urban gradient. Riparian, local, and regional land use must each be considered to create a holistic management plan that effectively protects ecosystem processes. Water resource management should continue to focus on the preservation of vegetated riparian areas to naturally abate increased flood flows and NPS pollution loads often associated with watershed development. Buffers ultimately serve as the final defense against stream impairment as impacts in a developing watershed reach critical levels that threaten the health of aquatic ecosystems. Our work suggests that upstream local land management to reduce impervious cover both longitudinally and laterally near stream channels is the next most important consideration for the protection of aquatic habitat.

More work is needed on the spatial scales that have the greatest effect on stream health in order to facilitate more effective protection of water resources. However, the implementation of the findings of this important line of research currently seems hampered by societal resistance to change to preserve the integrity of urban streams. For example, land use zoning regulations need updating as they often mandate increased amounts of impervious cover (Stone, 2004). Municipalities should promote moderate to high-density residential living, away from stream corridors, that has less impervious cover than low-density models. Landowners adjacent to streams should be contacted to stop yard waste dumping and to promote the maintenance of naturally vegetated riparian buffers to reduce local streamside impacts (Booth *et al.*, 2004). Porous pavement has been shown to limit stormwater runoff, reduce NPS pollution delivery, and be durable enough for moderate automobile use (Brattebo and Booth, 2003) and thus should be used when appropriate conditions and ample funds are available. Finally, we recommend that the critical task of riparian and local land management be conducted within the watershed context in order to facilitate a multiscale, tiered approach to water resource management. Smaller units that can be readily influenced, say due to restoration practices or regulatory activities, are collectively assessed and adaptively managed within a framework at a larger spatial scale.

CONCLUSIONS

We observed a critical level of 5% TIA, above which water quality declined, macroinvertebrate assemblage health was reduced, and instream habitat was impaired. Instream conditions worsened with increasing impervious cover and eventually plateaued in a degraded state at and above 10% imperviousness. The WQI tuned for this study effectively identified stream reaches impacted by urban NPS pollution and was shown to be strongly correlated with some measures of biological community health. The index appears to be a useful tool to prioritize land use management decisions and to set stream restoration water quality targets in urban watersheds in our study region.

We found imperviousness in the 100-m riparian buffer in local contributing areas to have the strongest relationship with instream parameters. Water and habitat quality had a relatively consistent strong relationship with TIA across each of the four spatial scales of investigation, whereas macroinvertebrate metrics produced noticeably weaker relationships at the larger scales. Our results confirm (e.g., Levin, 1992; NRC, 1999) the protection and restoration of aquatic ecosystems must incorporate a multiscale approach.

Even with the identification of a potential development threshold of 5 to 10% TIA, our work on the spatial scale and location of impervious cover supports the theory of a multidimensional nature of urbanization in relation to stream degradation (e.g., Booth *et al.*, 2004). We thus believe that the use of TIA alone is not recommended for predicting stream health and making land management decisions. Nevertheless, this indicator variable of urbanization is useful as guide that should initiate concern for, and additional study of, stream quality and the potential causes of urban stream degradation at levels above 5% impervious cover.

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